Ultrafast Diagnostics for Relativistic Laser-Plasma Experiment

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Laser-plasma experiment is becoming one of the methods to understand astrophysics. Laser-generated fast plasma can generate the fundamental plasma dynamics in the universe such as collisionless shock, which is one of the most promising candidates for cosmic ray acceleration. Previous research demonstrated the collisionless Weibel shock, which is generated in relativistic plasma flow (e.g., gamma-ray burst afterglows, active galactic nuclei, and pulsar wind nebulae), using a long-pulse (nanosecond) high-power laser system. The specific features of the Weibel shock were confirmed: the filamentary structure of plasmas and the non-Maxwellian energy spectrum of accelerated electrons. However, the long-pulse laser experiments have a few problems including the small shot numbers and the low laser intensity, which hinders the detailed parameter search and the ion acceleration, respectively. We apply the relativistic short-pulse (sub-picosecond) high-intensity laser to the collisionless Weibel shock experiment to solve the problems mentioned above. Numerical simulations demonstrated that the fast electrons generated through the laser-matter interaction trigger the return currents inside the bulk of the plasma. The counter-streaming electrons (fast electrons and return currents) result in the Weibel shock. It is indispensable to develop ultrafast (sub-picosecond) diagnostics to understand the real plasma dynamics.

To obtain the temporally resolved charged particle energy spectrum and Weibel filament structure, we develop the electro-optic (EO) sampling and the small-angle x-ray scattering (SAXS) methods, respectively. In short, the former converts information of an electric field (e.g., the strength and the temporal evolution) into a modulation of a polarized laser pulse via a nonlinear crystal, and the latter is a diffraction at a small scattering angle. Applying the EO sampling method to the detector of the accelerated charged particles in the setup of the charged particle spectrometer, in principle, it is possible to obtain the temporal evolution of the energy spectrum with sub-picosecond resolution. The SAXS measurement using the x-ray free-electron laser (XFEL) is promising to obtain the evolution of the Weibel filaments with nanometer and femtosecond spatiotemporal resolution. Moreover, the developed ultrafast diagnostics are versatile and provide a platform to conduct the laser experiment at relativistic regime.

We succeeded in conducting single-shot spatiotemporal EO sampling of an electric field around a relativistic electron beam using an echelon mirror for the first time. The echelon mirror has a step-like mirror surface and an injected probe pulse is divided into multiple beamlets with certain delays after the reflection, which enables the temporal measurement. This technique is promising for the temporally resolved charged-particle energy spectrometer. The obtained spatiotemporal electric field profile shows the contraction of the electric field in the beam propagation direction, which demonstrates the Lorentz transformation (LT) of electromagnetic potential vectors. The estimated electron beam sizes in the transverse and longitudinal directions are obtained by the electric field profile; the longitudinal size is much smaller than the transverse one, which implies the Lorentz contraction of the beam itself. These results are novel experimental evidence of special relativity and one of the rare experimental visualizations.

The SAXS diagnostics is developed at SACLA XFEL in Japan. We conduct the pump-probe experiment using the high-intensity (HI) short-pulse laser and the XFEL beam. To evaluate the performance of the SAXS for the laser-generated plasma, we used the silicon wire assembly target, which emulates the Weibel filaments. We ionized the wires by injecting the

HI short-pulse laser pulse into them and obtained the temporal evolution of the columnar plasma expansions. We confirmed that the SAXS method can be applicable to the three-dimensionally structured plasma. We introduced the layered filter system, which attenuates a part of the XFEL beam profile, instead of the beamstop. This system allows us to access the SAXS signal around the original XFEL beam, which contains important information on the plasma structures such as Weibel filaments.